MUTUAL INFLUENCES OF DIGIT SPAN RECALL AND CONCUSSION HISTORY DURING INTERCEPTION OF A MOVING TARGET

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ABSTRACT

Kou Yang: Mutual Influences of Digit Span Recall and Concussion History During Interception of a Moving Target
(Under the direction of Dr. Adam Kiefer)

Second injury risk following concussion merits improved return to play assessments. Two studies examined deficits in athletes with a concussion history (Cx): 1) a secondary analysis to investigate an area under the curve (AUC) assessment for cognitive recall; 2) a dual-task paradigm (cognitive recall with moving target interception) in virtual reality to investigate perceptual-motor deficits. AUC was lower relative to Cx (2.523 ± 0.537 vs. 2.884 ± 0.599), $t(48) = 2.148$, $p = .037$. Single-task recall resulted in a higher AUC (1.584 ± 0.330 vs. 1.418 ± 0.347), $F(1,28) = 6.82$, $p = .014$, independent of group. Single-task target interception led to a more efficient angle of interception ($0.185° \pm 0.239°$) compared to dual-task 9-digit-span recall ($0.551° \pm 0.757°$), $t(28) = -4.031$, $p = .001$. These results demonstrate the importance of novel indices of perceptual-motor and cognitive ability as a first step toward improved concussion return to play sensitivity.

To my grandmother
You were my biggest inspiration and greatest supporter.

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CHAPTER 1

INTRODUCTION

Concussions are a subset of traumatic brain injuries (TBI) that have grown in concern and research interest due to their increasing occurrence across a multitude of sports.[12] The injury itself is considered a functional rather than a structural injury as it affects each athlete differently.[3] To determine how each athlete is affected, a battery of neurocognitive, motor and symptom assessments are typically administered to inform treatment strategies for efficient and safe return to play. Typically, the treatment of these injuries commits athletes to physical and cognitive symptom limited activity, the first of the six-stage return to play. Following symptom resolution, athletes then typically progress through more exertional activity before being cleared for return to play if symptoms do not reoccur.[4] Despite the consistent implementation of these systematic protocols following an initial concussion injury[5], epidemiological studies indicate these athletes are at an increased risk of both secondary concussion injury and lower extremity musculoskeletal injury up to one year after the initial injury and clearance for return to play.[6] These data indicate that deficiencies may exist beyond those that are typically assessed and detected via standard neurocognitive, symptom evaluation, and static balance assessments. Thus, a potential factor in injury risk may lie in the lack of assessments that take place in a functional, sport-like environment, as these might uncover potential perceptual-motor and cognitive deficits that persist following concussion injury.

An athlete's perceptual-motor behavior is critical to how efficiently they are able to respond to the various challenges they face during sport competition.[7,8] Perceptual-motor behavior is an individual's ability combine both perception to their motor output. That is, to successfully perform on the playing field, athletes must remain sensitive to the appropriate perceptual information and act accordingly. For example, for a soccer player to make a successful pass they must first perceive their environmental dynamics and detect opportunities (perception). They must then coordinate their motor output to place the ball properly (motor).[9] The presence of perceptual and motor deficits therefore have negative implications for performance[7,10] and, ultimately, place athletes at greater risk for injury.[10] These deficits are known to be present following concussion injury and may persist for months or years following clearance to return to play.[11–18] With regard to perceptual deficits, a study of children demonstrated sensitivity with complex visual information following concussion injury for up to 12 weeks post injury.[12] Another study found that undergraduates (male age 23.83±4 years; females 22.80±3.5 years) with a concussion history had visual working memory deficits on average 5.6±4.8 years post injury,[13] and young adults between 20 and 29 years old had reduced visual processing on average 6.7±3.9 years post injury.[11] These findings parallel a similar disruption to auditory processing, another piece of perceptual information, following concussion on average 6.75±2.4 years post injury.[14] Motor deficits are also well documented following concussion, with individuals exhibiting less adaptive postural control during quiet standing on average 48.7 ±64.85 days post injury[16], reduced dynamic balance up to twelve weeks post injury[15] and increased spatial attention deficits up to 28 days post injury.[17] The presence of these perceptual and motor deficits in patients with a history of concussion, across a variety of age groups, provides the basis for a potential causal link to subsequent concussion injury and an increased risk of secondary musculoskeletal injury.

While there is open debate regarding the specific factors that lead to these post-concussion perceptual and motor deficits, a key contributor could lie in the pathophysiology and, specifically, diffuse axonal injury—a common insult following acute concussion injury. In fact, one key mouse model that is resistant to axonal degeneration indicated that the mice maintained spatial memory, motor balance, and visual function after a blast-mediated injury.[19] Additionally, pharmacological studies on animal models suggests certain chemical compounds that aid in blocking axonal degeneration also preserve learning, memory, and motor coordination.[20,21] While additional studies are needed to investigate how well these findings translate to humans, these animal studies provide a compelling link between diffuse axonal injury and changes to perceptual and motor capabilities following concussion injury. However, what remains unknown is how these deficits may be further impacted by other environmental factors such as exercise exertion and cognitive demands as the athlete navigates a variety of performance contexts following their return to play. This is a potentially critical component to understanding the role of perceptual and motor function in the context of sport performance and sport-related injury.

The environmental context has often been neglected in concussion research despite its obvious importance. In fact, studies on gait,[22,23] balance,[24] memory,[25] and dual-tasks (a testing paradigm requiring completion of a motor task while simultaneously performing a cognitive task)[23,26] are typically conducted within a laboratory setting to control for extraneous factors. While this type of research has proven useful for uncovering underlying deficits that are present, and persist, following concussion injury, they are limited in their ability to fully capture the interacting perceptual-motor processes that promote successful, injury-resistant sport performance. A more comprehensive approach should conduct these assessments in sport-like task contexts. This would allow researchers to better identify and link potential deficits to functionally meaningful performance in the competitive sport environment.

A potential solution that allows for laboratory control while providing more realistic environmental simulation is virtual reality (VR). The utility of VR goes back to the mid-twentieth century and its application for safe flight simulation training and the successful transfer of learned skills to the real world.[27–29] Specific to concussion, VR has been used to assess the role of visual disruption and postural stability using relatively simplistic visual environments.[30–32] It has also been validated as a balance module for clinical concussion assessment[32] and a study by Newell and colleagues found that VR destabilizing visual field motion induced postural dysfunctions in 30 day post-concussion participants that were not seen in standard balance tests.[31] This sensitivity to balance deficits was further explored by Slobounov's research, which detected residual balance and visual dysfunctions in 'asymptomatic participants' when VR was incorporated with EEG.[30] Such results indicate that VR modules could aid in postural stability assessments[33,34]; however, while the results of these studies reveal how an environmental context could underlie changes in behavior, VR has yet to be deployed for the replication of sport-like environments in the context of concussion. This is not the case in other sports medicine contexts, the results of which can be used to support VR as a useful tool for evaluating post-injury deficits.[35] For example, one notable study has shown that a less sterile, sport-like environmental context presented in VR can change motor behavior outcomes. Specifically, during the performance of a simulated soccer corner kick header task in virtual reality (VR), female soccer athletes exhibited significant changes in lower-limb injury risk landing biomechanics compared to a real world drop vertical jump task performed in a controlled laboratory setting.[36] Results such as this indicate that traditional laboratory settings may not adequately index the combined perceptual-motor changes relevant to competitive sport performance. Thus, to better elucidate the underlying mechanisms that lead to second injury risk to ultimately improve patient outcomes, assessments should replicate sport-relevant environmental contexts while experimentally controlling for functional perceptual-motor demands.

Developing a sport-relevant assessment that controls for perceptual-motor and cognitive demands of sport is not an easy proposition, and utilizing such an approach requires a theoretical framework that can account for perceptual-motor behavior across dynamic performance contexts. Behavioral dynamics is one such framework, and was first introduced by Warren and colleagues as a computational approach for modeling perceptual-motor behavior within the broader human-environment system.[37] This modeling strategy treats the athlete (in this case) and the environment as a pair of dynamical systems connected via vectors of environmental and athlete state variables. That is, changes in the state of the environment are a function of its current state and the external forces produced by the athlete on the environment, while changes in the state of the athlete are a function of the athlete's current neuromotor state and current values of information (i.e., perceptual) variables. This means that the environment is always governed by the laws of physics relating changes in environmental states and forces, and that the athlete's behavior is driven by a control law that relates informational variables with changes in neuromotor states. In this way it allows for a mathematical tracing of the perceptual-motor cycle that generalizes across movement contexts.

Importantly, this modeling approach has been successfully applied to identify the pertinent (perceptual) information variable(s) and the resultant action(s) (i.e., motor variables) that arise via the time-sensitive interaction of an individual's spatial positioning in response to environmental stimuli across a range of goal-directed navigation tasks.[38,39] One such task context utilized in this approach requires an athlete to intercept a target that is moving at a constant velocity.[40] In this context, efficient interception performance was successfully modeled via a constant bearing angle

(β) solution, which is based on an informational control law to reduce the change in the bearing angle ($\dot{\beta}$)—i.e., the angle at which the athlete is heading relative to the target—over the time needed to intercept the target (see Figure 1). Thus, a smaller amount of variability (i.e., lower standard deviation) observed for $\dot{\beta}$ indicates more efficient interception performance, and vice versa. It also provides a theoretically grounded index of perceptual-motor efficiency.[41] Despite the potential utility of this approach for the evaluation of an athlete's readiness to safely return to play, the behavioral dynamics approach (and the constant bearing angle model, specifically) has not been utilized in more dynamic sport-like contexts or for post-concussion assessment.

While perceptual-motor efficiency is integral to successful athletic performance, athletes must also simultaneously maintain efficient cognitive performance as they continuously recall and process strategic information to make decisions during competition.[26] Failure to do so likely exacerbates existing perceptual-motor deficits and may further increase injury risk. Much like the identified post-concussion perceptual-motor deficits, various cognitive deficits have also been identified following concussion.[25,42,43] For example, there is evidence of increased simple and choice reaction time, verbal and visual memory deficits within twenty-four hours of injury,[25] alterations in resource allocation with working memory assessments on average 26.9 days post injury,[42] and decreased working memory performance has been observed up to 90 days post injury.[43]

As working memory is the temporary storage system that holds information that will be updated or manipulated (e.g., long division[44] or strategy-based games like chess[44,45]), disruption to this process could reasonably impact sports strategic planning as well. One study on working memory utilized an n-back test in conjunction with fMRI[42] and found that healthy and previously concussed groups did not differ in tasks performances, but had significant differences in brain resource allocation.[42] Specifically, in the previously concussed group there was increased brain pattern activation during the moderate load and decreased activation during the highest processing load. These results indicate that, potentially, the n-back working memory assessment may not have been sensitive enough to detect these underlying resource allocation changes.

A more commonly used assessment for working memory is the digit-span recall task, where participants recall numbers in a certain sequential order.[45] This assessment was utilized by Well and colleagues who advocated that modifications in traditional scoring of the digit-span recall task could also improve the validity of measuring working memory.[45] Potentially, utilizing a common working memory assessment (digit-span recall) and applying an improved scoring method could increase the sensitivity and validity of the working memory assessment and capture these underling brain resource allocation patterns that have been seen across various workloads. A novel approach that could improve the validity could be to assess the adaptable performance of patient scores across various cognitive loads (i.e., more digits to recall) rather than traditional scoring. The framework of such an analysis originates from biological studies on organism adaptability to their surrounding environment.[46] Analyzing performance based on adaptability could potentially be a more sensitive measure of an athlete's subclinical deficits and readiness to return to play.

Subclinical deficits are even more pronounced when assessed as part of a *dual-task* paradigm—i.e., participants simultaneously perform a motor task (e.g., walking) and a cognitive task (e.g., simple arithmetic). This paradigm allows for the examination of the interacting cognitive and motor processes rather than the assessment of each in isolation, and while this does not replicate the performance environment, it is a step closer to the complexities with which an athlete is faced during competition. For example, dual-task assessments indicate that, following concussion, individuals exhibit decreased gait velocity,[47] changes in postural stability,[23,26,48] and decreased cognitive task accuracy.[48] The identified changes in these dual-task assessments compared to the single-task performance persisted beyond standard clinical recovery times, up to two months following injury.[26] This inefficiency of completing cognitive and physical tasks simultaneously[26,48] may directly correlate to post-injury changes in perceptual-motor ability during sport participation, ultimately leading to increased risk of injury. The presence of these cognitive deficits, in combination with the perceptual and motor deficits discussed earlier, represent a perfect storm of functional inefficiencies that interact to place athletes at significant risk for secondary injury following concussion. However, even as these dual-task studies have begun to tease apart the interacting effects of cognitive and motor performance in this population, they are limited in their ability to fully capture the dynamic, time-sensitive and context-specific perceptual-motor and cognitive interactions that take place during sport. As a result, there is a need to further examine perceptual-motor and cognitive performance together, within a dynamic environmental context, to better understand the role each play in post-concussion injury risk and recovery.

Concussion reinjury[5] and increased risk of lower extremity injury[6] continue to be problematic when athletes return to play. Addressing this issue therefore requires a comprehensive approach to piece together all previously discussed factors: perceptual-motor behavior (via behavioral dynamics), cognitive performance, and a functional sport-specific environment. By replicating a sport environmental context that requires functional perceptual-motor behavior, while simultaneously controlling for cognitive demands, one could more closely replicate on field demands that an athlete would see and better identify the interplay between these potential component causal mechanisms. Additionally, assessing adaptable performance across workloads rather than traditional scoring performance at each workload could potentially yield a more sensitive measure of an athlete's subclinical deficits and return to play readiness. Therefore, the purpose of this study is to simulate a sport-like environment (through the use of VR) in order to examine perceptual-motor and cognitive deficits that are known to persist following concussions.[24,42,43,49–54] To achieve this, participants were tasked with a novel, laboratory-based *dual-task perceptual-motor* assessment where they completed a reverse digit-span task (cognitive component) and a moving target interception task (perceptual-motor component) in VR independently (single-task) and at the same time (dual-task). The reverse digit-span task is a commonly used cognitive assessment for working memory performance that requires participants to accurately recite a series of digits and recall those digits in the reverse order to test working short term memory.[55–57] This task is well validated, and provides an objective assessment of working memory relative to workload, in the form of longer series of digits. It also lends itself well to a dual-task assessment paradigm.[58,59] The integration of a dual-task perceptual-motor assessment within a VR environment would, for the first time, index the interacting effects of cognitive and perceptual-motor deficits that may negatively impact athletes' safety and performance when returning to play following concussion.

Clinical Significance

A functional concussion assessment that simulates a sport-like environment through VR may reveal perceptual-motor and cognitive deficits that linger during a dual-task perceptual-motor assessment, which would provide a quantitative metric that will help clinicians and researchers bridge the gap between lab-constrained test and on field readiness.

Research Questions

RQ 1: Do individuals with a concussion history exhibit more adaptable performance across cognitive loading during single-task digit-span recall compared to no concussion history controls based on a secondary analysis of historical data?

RQ2a: Do individuals with a concussion history exhibit more adaptable performance across cognitive loading during single-task and dual-task digit-span recall and target interception compared to no concussion history controls?

RQ2b**:** Do individuals with a concussion history display differences in perceptual motor efficiency as indexed via differences in the standard deviation in the change in bearing angle ($\dot{\beta}$) during interception of a moving target compared to those without a concussion history?

RQ2c: Do individuals with a concussion history display differences in perceptual motor efficiency as indexed via differences in the standard deviation in the change in bearing angle ($\dot{\beta}$) during interception of a moving target while also performing a digit-span recall task compared to those without a concussion history?

Hypothesis

H1: Individuals with a concussion history will exhibit less adaptable performance scores during single-task digit-span recall compared to no concussion history controls across workloads.

H2a: Individuals with a concussion history will exhibit less adaptable performance scores during single-task and dual-task digit-span recall and target interception compared to no concussion history controls across workloads.

H2b: Individuals with a concussion history will exhibit a larger mean standard deviation in the change in bearing angle ($\dot{\beta}$) during interception of a moving target compared to those without a concussion history.

H2c: Individuals with a concussion history will exhibit a larger mean standard deviation in the change in bearing angle ($\dot{\beta}$) during interception of a moving target in the presence of a digit-span recall task compared to their own performance during the single task interception and compared to those without a concussion history.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Concussion Injury

A concussion injury is a subset of traumatic brain injury (TBI), often used interchangeably with mild traumatic brain injury (mTBI)[1,60] and was recently defined at the 5th international conference on concussion in sport as induced by either a direct blow to the head or via indirect biomechanical forces that originate from other parts of the body and transmit to the head.[3] Therefore, the result is not a structural deformity—no abnormal structural findings are seen during standard neuroimaging—but a functional injury through the presentation of neurological impairment that often resolves spontaneously.[3] This resolution is typically 10-14 days for adults and 4 weeks for children.[3] However, it is possible for symptoms to persist beyond this common recovery timeline.[3] Concussion injuries are each uniquely different and may present themselves through a wide range of signs and symptoms without the occurrence of an individual losing consciousness.[3] The sideline evaluation and diagnosis of concussion is based on recognition of a direct head injury, changes in cognitive and cranial nerve function (assed via a battery of clinical test and questions associated with each cranial nerve—i.e., ability to smell, identify a number of fingers, pupillary light reflex, ocular movement, fascial sensation, fascial motor activation, ability to hear, ability to swallow, activation in neck stabilizers and togue movement),[61] and changes in balance.[3] It is recommended that neurological serial assessments be routinely taken as part of an athlete's overall management, especially as concussion symptoms may be delayed upon initial evaluation.[3] Clinical neurological assessments may include a variety of components: cognitive/mental status, oculomotor function, sensorimotor, coordination, gait, and vestibular function.[3] Similarly, neurological assessments often include a multi-modal evaluation of symptoms via tools such as the Sport Concussion Assessment Tool 5 (SCAT5), and include questions assessing headache, head pressure, neck pain, nausea, dizziness, blurred vision, balance deficits, sensitivity to light, sensitivity to noise, sensations of being 'slowed down,' trapped 'in a fog,' 'not right,' difficulty with concentration and remembering, fatigue, confusion, drowsiness, increased emotion, irritability, sadness, anxiousness, and difficulty falling asleep.[62]

Cognitive and balance deficits, specifically, are common post injury and typically resolve within the first two weeks after injury.[3] Within 24 hours of injury, deficits in cognitive ability include slower response times during both simple and choice reaction time assessments, and reduced verbal and visual memory performance.[25] Impairments to postural stability are commonly present between 3 and 7 days post injury[24,63], but have been identified in asymptomatic individuals beyond six months following an initial concussion injury.[64] Thus, in addition to acute short term cognitive[25] and postural stability deficits,[63] of equal concern are the possible long-term deficits that can interfere with the safe return to play of athletes following concussion injury. These long-term deficits potentially manifest as an increased risk of both secondary concussion injury[5] and lower extremity musculoskeletal injury up to one year after the initial concussion injury and clearance for return to play .[6] This overall breadth of symptomology[3,25,62,63] and increase risk of future injury[5,6] is even more concerning in light of the high prevalence of concussion injuries that continue to increase each year.[65]

2.1.1 Epidemiology of Concussion

Various studies collectively have indicated an increase in the prevalence of concussion injury[65,66], which parallels an increase in sport participation.[67] According to a recent study by the National Electronic Injury Surveillance System on sport and recreational related TBI treated in the US emergency department from 2001 to 2012, approximately 3.42 million emergency department visits were related to sport related and recreational TBI;[68] however, this likely underestimates the actual impact being as high as 3.8 million undiagnosed concussions occurring each year.[60,69]

When considering injury rates in both high school and collegiate sports, the continuous rise in concussion injuries is concerning. A prospective study conducted by Lincoln et al. demonstrated that over an 11 year period there was a 15.5% increase in the incidence of sport-related concussions across 12 high school sports between 1997 and 2008.[65] A study by Gessel and colleagues investigated both high school and collegiate athletics via the National Collegiate Athletic Association Injury Surveillance System (NCAA ISS) and the High School Reporting Information Online (RIO), respectively, indicated that during a one year period collegiate athletes had higher rates of concussion than high school athletes (.43 per 1000 athlete exposures compared to .23 per 1000 athlete exposures respectively).[70] Importantly, the NCAA reported that the number of male and female collegiate athletes across all three sport divisions has nearly doubled over the last 40 years:[67] data that compound the observed increase in concussion injuries. While Lincoln et al. attributed the 11-year increase in concussion injury to one of two causes—either increased concussion detection or increased injury occurrence—it is likely a combination of the two.[65] Furthermore, it is important to recognize that these injuries occur across all contact sports and are not restricted by gender[2], as Lincoln et al. also indicated.

Specifically, across 25 public high schools, males who participated in football had the highest incidence rate (.60 per 1000 athletic exposures), but the second highest incidence rate was seen in females who participated in soccer (.35 per 1000 athletic exposures).[65] This data is supported by both the RIO and NCAA ISS data indicating the highest concussion rates in football and soccer across both high school and college groups.[70] All of these data demonstrate that, despite the increased efforts in concussion research to prevent and treat these injuries, injury rates have not decreased across youth, high school, collegiate[65] or professional sports[65,66] and the potential long term negative implications of these injuries are still not fully understood.

In addition to the large prevalence of concussion injury, there is a second growing body of evidence indicating that secondary injury risk is also increasing following concussion. An epidemiological study on high school and collegiate football players found that players who sustained a concussion during their competitive season were three times more likely to sustain a subsequent concussion during that same season compared to players who did not sustain a concussion injury.[5] Similarly, collegiate athletes who sustained a concussion across 13 different sports, including field and contact sports, were 1.97 times more likely to experience a lower extremity musculoskeletal injury up to one year after the initial concussion injury compared to matched controls who did not sustain a concussion during the season.[6] Combined, these epidemiological studies indicate that the current protocols for returning athletes to play after injury are not effective and, importantly, may not be targeting the appropriate risk factors underlying secondary injury.

2.2 Neurophysiological mechanisms

Return to play protocols do not directly investigate neurophysiology and are predominantly based on symptomology[3], which does not always consider the complexity of neurophysiological mechanisms and extended physiological recovery that could lead to functional deficits. Physiological mechanisms implicated in concussion have been described by the neurometabolic cascade theory derived from animal models.[71,72] This theory states that, as a result of direct or indirect forces to the head, microstructural damage may occur to the neural tissues which, in turn, impairs axonal transport and creates an ionic imbalance.[71,72] Specifically, the lipid membrane of neuronal cells experience mechanoporation (creation of sublethal pores in the membrane) from the onset of forces causing an influx in sodium and calcium ions, and an efflux of potassium ions which depolarizes the cell.[72] To restore the cell to the original state of homeostasis, there is an immediate increase in metabolic demand as ionic pumps require an increase in adenosine triphosphate (ATP) to pump ions into and out of the cell.[73] However, in addition to the increase in energy demand, there is also a reduction in cerebral blood flow that results in an unequal energy demand and supply.[74] This increase in metabolic demand spikes initially, but then dramatically decreases for a period lasting up to ten days.[72,73] This cascade of physiological alterations is concerning as it can negatively impact perceptual-motor ability. If these physiological changes do not recover timely and properly, it could lead to persistent perceptual-motor deficits.

Axonal dysfunction is also a major component to the current theory of pathophysiology in post-concussion injury, with recent animal studies evidencing diffuse axonal injury as a major contributor to perceptual-motor deficits.[19,75–77] Specifically, Yin and colleagues[17] investigated the relation between performance measures of spatial memory, motor balance and visual function and axonal degeneration after a blast-mediated traumatic brain injury in wild and Wallerian degeneration slow strain mice (WIdS) known to be resistant to axonal degeneration post injury.[19,75–77] The results indicated that, as expected, the WIdS mice resisted axonal desecration after blast-mediated injury, and that their performance in all three areas was preserved.[19] This demonstrates a potential mechanistic link between axonal degeneration and neurobehavioral complications.[19] Pharmacological studies on mice have also shown that neuroprotective chemicals, such as the P7C3-A20 compound, can block axonal degeneration following simulated head trauma and also preserve learning, memory and motor coordination performance.[20,21] Similarly, increasing nicotinamide adenine dinucleotide (NAD+) levels (a precursor to Adenosine-Triphosphate, or ATP, used for energy)[78,79] by administering nicotinamide post-injury improves limb asymmetries[80] and working memory in rats.[78] In one such study, a traumatic brain injury was induced in rats through intranasal administration of NAD+ and the rats exhibited reduced hippocampal neuronal death following the administering of 20mg/kb body weight of nicotinamide immediately after induced injury.[81] The use of a poly (ADP-ribose) polymerase-1 inhibitor (an enzyme known for its role in NAD+ depletion and subsequent neuronal cell death[82,83]) also prevented NAD+ depletion[83] and improved motor function recovery in mice with induced traumatic brain injury via controlled cortical impact when the inhibitor was administered as late as 24 hours post injury.[82] These studies suggest diffuse axonal injury is implicated in spatial memory, motor balance, and visual dysfunction and it highlights the importance of building a greater understanding of the perceptual, motor and cognitive deficits that result following this pathophysiological cascade after a concussion injury.

2.2.1 Extended Physiological Recovery

Following initial concussion injury, the typical resolution of symptoms, cognitive function, and postural-stability deficits occurs within seven days;[24] however, a recent neurophysiology study has shown that physiological recovery may extend beyond this seven day period of clinical asymptomatic recovery and longer than what current clinical measures have previously identified.[84,85] Gosselin and colleagues utilized electroencephalography (EEG) to investigate event-related potentials during performance of an auditory perception task by symptomatic (15.1 +/- 16.6 weeks since injury) and asymptomatic athletes (5.3 +/- 3.1 weeks since injury) who recently suffered a concussion.[85] They found that both groups of athletes had similar reductions in EEG waveforms associated with automatic information processing, cognitive processing, and attentional processing during task performance compared to healthy controls. Additionally, there were no differences in reaction times between the asymptomatic and symptomatic groups,[85] which calls into question the validity of return to play guidelines based on symptomology.[85] This also highlights how physiological alterations likely extend beyond overt symptoms and has implications for return to play safety for athletes—e.g., early return to play prior to complete neurophysiological recovery could expose athletes to increased risk of secondary injury due to decreased athletic performance which could lead to an increased sport-related accidents.[84,85] With emerging evidence that there is extended neurophysiological recovery[84,85] and that neurophysiological changes are potentially linked to axonal disruption and, ultimately, to perceptual-motor dysfunction in spatial memory, balance, and visual dysfunctions,[19,75–77] one could postulate that there likely exists an extended perceptual-motor dysfunction that is not being identified in concussion patients by current assessment protocols, and that the failure to identify this dysfunction is a primary contributor to the increased injury risk following concussion.

2.3 Limitations of Current Return to Play Assessments

Despite the preponderance of evidence indicating a complex and extended neurophysiological response to concussion injury, and the potential link to underlying perceptual-motor deficits, current guidelines advocate for a standardized symptom-based approach for return to play protocols.[4] Accordingly, the typical six stage return to play progression is as follows. First, athletes must go through a period of symptom limited physical and cognitive rest until physical, cognitive and neurological self-reported symptoms have resolved. Once this milestone has been reached, athletes next enter the second stage of the progression by introducing exertional activity starting with light aerobic exercise (e.g., walking, swimming, stationary cycling at <70% of maximum permitted heart rate) and then advance to sport-specific exercise (e.g., skating drills in ice hockey or running drills in soccer), noncontact training drills with a systematic increase in drill complexity, full contact practice, and finally return to normal game play. The athlete advances to each subsequent stage only if they are able to complete each functional activity without a return of symptoms.[4] Despite a strict adherence to this systematic graduated return to play based on individual symptom presentation, athletes continue to remain at high risk for second injury following a return to competition.[5] The source of this increased risk could lie in the limitations of concussion assessment: the failure to identify perceptual-motor dysfunction using neurocognitive assessments and their potential lack of transfer to sport specific contexts.

2.3.1 Symptom Inventory and Neurocognitive Assessments

Neurocognitive assessments are a cornerstone to concussion treatment and aid medical professionals by providing an organized method for documenting the plethora of clinical domains often altered with concussion injury.[3] The SCAT5 is a great example of this. The SCAT5 is also a commonly used paper assessment that incorporates the Post-Concussion symptom Score (PCSS) while also assessing cognitive, neurological, and memory performance.[3] The PCSS is a subjective scoring scale that lists and quantifies the severity of a patients' concussion symptoms on a scale of 0 to 6 (0 or 1 no symptoms, 2-4 moderate, 5-6 severe)[86], and is validated to be associated with mild cognitive impairment.[86] However, there are limitations to this subjective questionnaire given its inability to assess underlying functional perceptual-motor deficits[62,87] as well as a lack of consideration of environmental factors that need to be reviewed.

Although the SCAT5 is very comprehensive and includes a neurological static postural control assessment,[62] it remains limited in its generalizability to the functional movement requirements of competitive sport. In fact, there is limited evidence that any of the eleven commonly used concussion assessments—ImPACT test, Cogstate Computerized Cognitive Assessment Tool (CCAT), modified stick-drop reaction time test, vestibular ocular motor screening, computerized neurocognitive software, vital signs, King-Devick test, and the satisfaction with life scale (SWLS)[87]—generalize to the functional deficits relevant to second injury during competitive sport. Neurocognitive testing has proven to be somewhat beneficial for the assessment of concussion injury, but lack application to sport specific context and do not account for the full complexity of perceptual-motor deficits that occur.

However, one portion of the SCAT5 could potentially provide a more relevant sport context with significant adjustments. The reverse digit-span task is a task adapted from previous work by Johnson et al.[55], which utilized a forward digit-span task to assess short term memory (a form of working memory), and was originally derived from the Wechsler Intelligence Scale for Children.[55,88] In this task, participants read a series of digits at a rate of one digit per second, and recall those digits back to the tester in the same order.[55] This task is commonly used to assess verbal short-term memory across populations[55–57] and the reverse digit-span task adaptation is included in the SCAT5 for concussion assessment. As the assessment is a measure of short-term memory,[55–57] it can have major implications in terms of remembering and processing strategic information during sport. While on the field, athletes must utilize their short-term memory to hold information like strategic plays and positioning. If their short-term memory is affected, they may have a difficult time retaining this relevant information that is needed into order to perform efficiently. This makes the reverse digit-span task a practical measure of one of the many the cognitive stressors athletes face during sports. If a perceptual component is added to this cognitive task, it could become a very practical perceptual-motor assessment.

In addition to adding a perceptual component, the reverse digit-span task may benefit from an improved method of performance scoring as prior studies have indicated that test modifications could increase test validity.[45] The task performance has been traditionally assessed in terms of recall accuracy.[45] However, athlete adaptability may be a better measure for return to play readiness than recall accuracy. If athletes require adaptability/flexibility to succeed in sport, cognitive performance should evaluate an athlete's ability to adapt across cognitive loads using a load-response type of analysis model. Such a model would provide a quantitative estimate of adaptability across workloads and ma have implications for concussion research.[46] A similar approach is used successfully in areas of biology: specifically in immunology studies, organisms are provided a vaccination (a small dose of an viral antigen) and the organism must adapt to cope with the virus.[89] A study by Hill and Kiefer have also utilized this to quantify behavioral adaptation responses when climbers were tasked with increasingly difficulty bouldering routes.[90] This resulted in each athlete having a load-response profile, calculated by the area under an athletes performance curve (i.e. how 'fit' they were in adapting to the increasing task difficulty/stress).[90] This model has yet to be applied to a concussion population, but could prove beneficial in profiling no concussion history and previously concussed athletes' adaptability to sport-like demands. To improve symptom inventory and neurocognitive assessments, perceptual-motor and sport specific contexts are necessary. If these are incorporated with the reverse digit-span task, in addition to improvements in the adaptability scoring, the result could be a perceptual-motor assessment that improves upon current neurocognitive testing limitations.

2.3.2 Lack of Transfer of Assessments to Sport Contexts

Improving current screenings and assessments require that we incorporate the systematic testing of functional movement and perceptual-motor deficits post-injury, and do so in a way that also considers factors related to competitive sport. However, current assessments of concussion lack consideration of a sport-like environment and how environmental factors influence an individual's cognitive and perceptual-motor behaviors. The importance of the influence such environmental factors can have on perceptual-motor behavior is highlighted by DiCesare et al.[36] and their study of injury-risk biomechanics with female soccer players performing a sport-specific task (jump landing after taking a header during a corner kick) within a simulated sport environment in virtual reality (VR). The results indicated that female soccer athletes exhibited significantly greater injury risk biomechanics related to lower-limb musculoskeletal injury—i.e., a reduction in hip and ankle flexion, hip abduction, and front plane ankle excursion—during landing within the soccer-specific VR task context compared to their performance on a standard lab-based drop vertical jump task. These results are some of the first of their kind, and indicate that traditional laboratory settings (and assessment batteries that do not take task context into account, more generally) may not adequately index the existence of perceptual-motor deficits relevant to competitive sport performance. Thus, to better elucidate the underlying mechanisms that lead to second injury risk to ultimately improve patient outcomes, assessments should be constructed to closely replicate sport-relevant environmental contexts while experimentally controlling for functional perceptual-motor demands. This would allow an increase in external validity (the replication of environmental stimuli allows for the assessment to be more generalizable) without the loss of internal validity (VR would continue to provide tight control and manipulation over all stimuli presented).

2.4 Perceptual-Motor Capabilities Following Concussion

Successful and injury-resistant sport performance requires that athletes be well attuned to their surroundings to respond effectively to varying situational contexts. A primary component that drives the efficient coupling between the athlete and their environment is one's perceptual-motor ability.[9,91] Therefore, the disruption to any component of an athlete's perceptual-motor behavior is detrimental to athletic performance and can increase injury risk. The idea of perceptual-motor deficits negatively impacting concussed athletes has been explored by Eagle and colleagues, who utilized the theoretical framework of direct perception to explain increased musculoskeletal injuries.[9,91,92] This framework was first introduced by James Gibson, who described that the performer (or athlete in our case) and the environment are linked in a continuous perception-action (i.e., motor) loop where the athlete is continuously perceiving opportunities for action, or affordances, of an environment.[9,91,92] Eagle leverages this theory to examine if concussion injury can disrupt the ability to detect and actualize affordances through a reduced capability of the athlete to perceive, recalibrate, attune, and explore the environment.[9] Calibration relates to an athlete's ability to adjust their own motor action,[9,93] attunement refers to changing which variable is being attended to,[94] and exploration relates to the movement of scanning the environment through rotation of the head.[95] As overestimation of one's ability have been associated with increased accidental injuries,[96] Eagle postulated that a disruption to any component of the process (i.e., perception, recalibration, attunement, or exploration), such as that which occurs post-concussion, would lead to the breakdown of this perception-action coupling and an increase risk of subsequent injury.[9] While this has yet to be formally tested, pieces of it are supported by the existing literature showing subclinical perceptual-motor deficits, and visuomotor deficits more specifically, post-concussion.

Perceptual-motor impairments have been demonstrated in concussed athletes in various studies. Classic examples of perceptual-motor impairments following concussion have been demonstrated through assessments that utilize a visual stimulus and subsequent motor reaction response experimental paradigm. For example, in a longitudinal study on attention in concussed participants, researchers found that concussed adolescents had increased reaction times when performing both the Attentional Network Test (ANT) and the Task-Switching Test (TST).[97] The ANT required participants to respond with a key press as quickly as possible to indicate which direction an arrow would be presented on a screen[97], while the TST required participants to switch between responding congruently or incongruently to a visual stimulus.[97] The concussed individuals exhibited disruptions in attention (and executive function) as seen through a decreased reaction time in both assessments up to 2 months post injury.[97] This prolonged perceptual-motor inefficiency has also been shown in a more functional task context. Lapointe et al. [53] examined seven participants who had sustained a concussion injury on average of 2.4 years prior to the study as they completed a jump cut maneuver as specified via the Flanker Test. Specifically, participants were instructed to jump forward with both feet onto a force plate and perform a cut in response to the direction of a visual arrow. The study revealed that the lower extremity kinematics of individuals with a concussion history exhibited decreased peak flexion and lower vertical center of mass during the assessment.[53]

Perceptual-motor stimulus-response tasks also extend to the areas of auditory, somatosensory, and vestibular perception, and studies on these areas have also indicated sensory deficits post-concussion injury. One such study investigated the auditory processing capabilities of no concussion history athletes and those with a concussion history.[14] Despite the fact that athletes with a concussion history were on average about 6.75± 2.4 years since their last injury, many had auditory processing deficits while preserving auditory detection. This meant that, regardless of concussion history, subjects had normal pure-tone detection at octave frequencies from 250 to 8000Hz but showed deficits in central auditory processing.[14] A study by Gagnon utilized the Pediatric Clinical Test of Sensory Interaction for Balance (P-CTSYB) to assess the capability of children 12 weeks post-injury to utilize visual, somatosensory and vestibular processing.[15] The results showed that when children were required to perform a tandem stance with their eyes-closed (requiring them to rely more heavily on proprioceptive information) and when they were on a foam pad (requiring them to rely more heavily on vestibular information) they performed worse than their healthy counterparts.[15] These studies emphasize the pervasiveness of these deficits across the various perceptual systems and how such deficits can negatively impact motor performance and, ultimately, may lead to increased injury risk.

2.4.1 Visuomotor Deficits Following Concussion

Visual information is often the most dominant information used to drive goal-directed behavior.[39] As a result, efficient integration and coordination of visual information with motor output(s) of the body (i.e., visuomotor behavior)[98] is perhaps the most crucial in generating appropriate and injury-resistant behavioral response, and disruptions to one or more of the components that underlie visuomotor behavior can have dire consequences for athletes on the field of play. In relation to concussion, studies have suggested that one's visual perception capability is commonly altered post injury. One study using EEG in young adults who were over six years removed from a concussion injury still exhibited reduced P1 amplitude (activation in the left-hemispheric parietal region of the brain)[11], which is suggestive of deficits in visual processing.[11] Similar findings have been shown relative to visual working memory in young adults, with deficits present over five years after concussion injury.[13]

Efficient visuomotor processing is also heavily reliant on efficient oculomotor control. Oculomotor control is the ability to move both eyes in rapid, stable, and coordinated succession so that objects can be fixated on accurately and efficiently.[99] Importantly, studies have indicated that a number of short- and intermediate-term oculomotor abnormalities can occur following concussion injury, including: eye convergence dysfunction,[51] increased anti-saccade duration (i.e., a measure of attentional suppression),[100] decreased saccadic eye movements,[49,50] less accurate smooth pursuit of moving targets,[49,50] as well as longer saccade latencies, greater fixation error, and larger initial fixation errors.[54] As the visual system is imperative for athletes to identify and track objects in their environment, even minor inefficiencies in oculomotor control—a primary driver of efficient visual attention—can have a negative impact on an athlete's visuomotor capabilities.

Together, these studies highlight the negative effects that concussions can have on perceptual-motor efficiency both in the short and long term. More importantly, these results necessitate the inclusion of perceptual-motor assessments, and specifically indices of visuomotor efficiency, in concussion return to play protocols. They also demonstrate how a disruption to the perception-action coupling (exemplified by the various visuomotor deficits[11–15,52,53,97,101]) likely leads to increased post-concussion second injury risk[5,6,9] However, even as several perceptual-motor tasks have been used to index concussion-related deficits, these tasks are limited in their generalizability to the dynamic task contexts representative of many contact and collision sports. Thus, an experimental framework is required that enables the quantification of perceptual-motor (i.e., visuomotor) efficiency within a dynamic sport-like task environment to comprehensively assess functional injury-risk deficits following concussion.

2.4.2 Behavioral dynamics

One framework that has demonstrated utility in quantifying visuomotor performance across a variety of dynamic movement contexts is *behavioral dynamics*.[102] Behavioral dynamics is broadly defined as the temporal and spatial connection, or coupling, between an individual (e.g., athlete) and their environment.[38,39] More specifically, behavioral dynamics states that an athlete's behavior is defined by the physical constraints of a given task and the informational (i.e., perceptual) variables used to guide behavior such that adaptive, goal-directed behavior emerges from the local interactions between an individual (governed by perceptual strategies termed *control laws*) and the environment (governed by laws of physics). The perceptual control laws are, therefore, regulated by the physical laws and formulated from the reciprocal relation between the individual and the environment. For example, athletes must continuously engage with perceptual information to inform on threats of opposing players, openings to supporting players, the goal line, and the safest or most efficient path to run, and then use this information to appropriately adapt their behavior and movements to continuously accommodate the changing environment. They do this by leveraging visual regularities that specify the dynamic relation between themselves and other locations within the environment over time. Therefore, the more effectively an athlete attends (or couples) to these regularities, the more efficient the athlete is in acting within the environment to achieve a given task goal.

One example of a control law, or perceptual strategy, in action can be observed in the behavior of an athlete navigating to successfully intercept a moving target. In this task context, the athlete minimizes the change in the athlete-target bearing angle ($\dot{\beta}$) for efficient interception as specified via visual information (see Figure 1).[41] This strategy can be summarized via a relatively simple heuristic: if the change in the bearing angle ($\dot{\beta}$) is nulled, and the target heading, speed and the athlete speed all remain constant, the athlete will eventually intercept the target. Thus, the average $\dot{\beta}$ over a given trial can be considered a summary measure of visuomotor efficiency in this particular task context, with lower values equating to more efficient performance. Fajen and Warren were able to operationalize this strategy via a series of experiments that were conducted in VR in order to control the presentation of the moving target (i.e., initial target position and speed).[37]

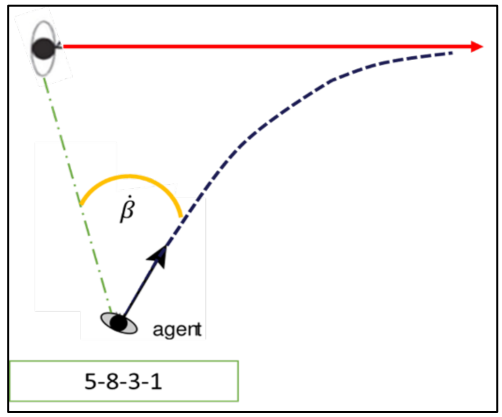

Figure 1. Dual Task Interception Diagram

VR is a useful tool to tightly control environmental characteristics, while at the same time simulating sport-like scenarios to better promote athlete behavioral responses, to assess visuomotor performance that translates to competitive sport. This is exemplified by one such study that utilized VR to assess athletes' perception of affordances in the sport of rugby. Specifically, participants were presented with gaps between two virtual defenders, and had to make perceptual judgments of whether they would be able to successfully pass between the two defenders without colliding.[103] VR has also been utilized to investigate the interception ability of handball goalkeepers, with the virtual environment used to control for changes in thrower kinematics to investigate subsequent goalkeeper reactions.[104] Both of these studies are examples of the utility of VR for examining specific sport contexts.

Specific to concussion, VR has also demonstrated utility for destabilizing the visual system to detect balance deficits beyond the typical ten day resolution of concussion symptoms—showing sensitivity in detecting deficits from fifteen days[30] up to thirty days post injury.[34] However, neither of these studies incorporated a sport-specific scenario or a task context that was necessarily transferable to competitive sport. So, while they demonstrate how VR can be used to control perceptual information in ways that would be impossible using real world environments.[24,30,31] they stop short of providing a functional task context to assess visuomotor deficits following concussion. In fact, to date no studies have utilized the behavioral dynamics approach to investigate the potential perceptual-motor deficits that could predispose an individual to second injury following concussion. This is surprising given the well-documented presence of both perceptual-motor and, specifically visuomotor, deficits following concussion.[24,42,43,49–54] Behavioral dynamics provides a novel framework for investigating functional outcomes based on underlying deficits that present following concussion and, therefore, can help shed light on the perceptual-motor mechanisms that underlie concussion re-injury[5] and lower extremity injury after returning to play[6] following initial concussion injury.

2.5 Cognitive Deficits Following Concussion Injury

In addition to the presence of perceptual motor deficits after concussion, an athlete's cognitive performance is often hindered post-injury as well. For example, the literature describes short-term cognitive deficits including increased reaction time, visual and verbal memory.[25] However, what may be more concerning is the long-term subclinical cognitive performance exhibited by patients following concussion. With neurophysiological assessments, children with a concussion history (2.1 ±1.9 years post injury) exhibited greater N2 latency, increased N2 amplitude, and decreased P3b amplitude as assessed via EEG during a flanker test compared to healthy controls. These results indicate subtle and pervasive difficulties in attention and cognitive control following concussion.[105] Neurophysiological changes in brain activity are also supported by neuroimaging (i.e., fMRI) studies that have examined working memory in adults after concussion. One study found no changes in working memory task performance between healthy and previously concussed individuals, but indexed a different pattern of brain activation in the concussed group with increasing working memory load indicating changes in resource allocation following concussion.[42,106] Similarly, an fMRI study on high school athletes showed reduced brain activity and worse performances on working memory task, indicating that youth athletes may be unable to engage compensatory brain recruitment strategies to maintain cognitive performance after concussion injury compared to their adult counterparts.[43]

2.5.1 Dual-Task Cognitive and Motor Assessments

One paradigm that has been utilized to examine the interplay between cognitive and functional motor performance is the dual-task paradigm. This paradigm typically requires participants to perform a motor task (e.g., gait) while simultaneously performing a cognitive task (e.g., arithmetic).[26] During gait dual-task assessments, the cognitive and motor tasks are thought to "compete" for resources, often resulting in changes in gait when compared to single task gait. This is known as dual-task cost.[107,108] In a systematic review by Büttner et al, 20 studies were reviewed that employed a dual-task paradigm (most studies were a question-answer cognitive task while walking) and found that individuals with a history of concussion experienced decreased walking gait velocity and increased frontal plane center of mass displacement up to two months following concussion during dual-task assessments, but not necessarily during single-task conditions.[26] Similarly, Lynall and colleagues looked into a dual-task consisting of tandem gait functional task (walking heel to toe as quickly as possible) and the Brooks Visuospatial Task (participants were provided with a 4x4 grid filled with digits and provided 1 minute to remember the position of each consecutive digit 1-8). They found that cognitive performance did not differ between groups. However, individuals with a concussion history had a slower tandem gait velocity. They concluded that subtle dynamic balance deficits existed with tandem gait functional task and there were implications of prioritization of cognitive task speed and accuracy while sacrificing gait velocity.[23] In a meta-analysis by Kleiner and colleagues also found a similar decrease in gait velocity and increased medial-lateral displacement. However, in contrast to Lynall, they found a decrease in cognitive task accuracy and performance by individuals with a concussion history during walking dual-task assessments.[48] Although the interaction between cognitive performance and motor performance is not fully established and show inconsistencies in cognitive performance while having consistent decreases in gait velocity,[23,26,48] these studies support how individuals with a concussion history must prioritize certain task during dual-task conditions as cognitive and motor tasks are "competing" for resources. This results in changes in gait and inconsistencies in cognitive performance.[23,26,48] Although these changes are subclinical, if individuals with a concussion history are exhibiting changes in gait during dual-task,[23,26,48] it is reasonable that complex cognitive skills required in sport strategy in combination to complex motor movements required by competitive sport would exacerbate these functional changes. This limited resource pool could predispose athletes to further injury risk, and dual-task assessments may be able to challenge participants in ways that better simulate competitive sport and more accurately identify potential deficits that may lead to increased second injury risk.

A variety of cognitive and motor tasks have been utilized and have shown similar deficits in motor function following concussion. For example, in a study by Cossette and colleagues, a concussion history group and a healthy comparison group were presented a battery of dual-task combinations consisting of four different cognitive task (i.e., no cognitive task, Stroop task, verbal fluency, and arithmetic) completed in tandem with three different walking tasks (i.e., straight line walking, walking while stepping over an obstacle, and walking followed by stepping down in elevation).[109] The results of the study indicated that, when performing all three cognitive tasks, the concussed group walked slower when they were required to step over obstacles compared to the control group.[109] Several other studies that employed visual or auditory Stroop tests showed that individuals with a concussion history exhibited more errors[110,111] and greater medial lateral center of mass displacement during walking compared to a healthy population.[112,113] Studies on concussion history compared to healthy populations have also investigated cognitive arithmetic,[107] reverse spelling task, and reverse month reciting[114] in combination with walking and turning motor task[107,114] and found changes in turning speed,[107] stride time,[107] and stride length,[114] and significantly lower cognitive task accuracy with spelling task and reverse month reciting.[114] These studies continue to reiterate how dual-task assessments are more sensitive to subclinical deficits than cognitive or motor tasks performed independently.[107,109,110,112–114] Further, although dual-tasks have been utilized extensively within a concussion population, they have yet to be utilized with respect to understanding the influence of cognition on perceptual-motor efficiency, nor have dual-task assessments been integrated into more functional sport-like environments.

Improving current concussion assessments requires an experimental paradigm that analyzes an athlete's cognitive adaptability while assessing functional deficits in a sport specific context. A dual-task assessment could integrate cognitive performance, perceptual-motor ability, while replicating a sport specific environment using VR. Therefore, we proposed a dual-task paradigm where cognitive performance adaptability will be assessed using a reverse digit-span task: a task that is already being used in the SCAT5. In conjunction, a target interception task would capture deficits in perceptual-motor ability. To accomplish this, VR will provide the flexibility to incorporate both cognitive and motor components while providing both internal validity in controlling extraneous variables and external validity by providing a sport specific environment.

Summary-Study Rationale

Concussions are a subset of traumatic brain injuries[1,60], which athletes typically recover from and return to play.[4,24] However, epidemiological studies indicate increased risk of secondary concussion injuries following a primary concussion injury[5] and an increased risk for lower extremity musculoskeletal injury.[6] This is concerning due to the increasing number of collegiate athletes[67] and questions the utility of current return to play assessments at minimizing injury risk.

Potential limitations that lead to this increase risk of concussion injury[5] and lower extremity injury[6] could reside in the inability of symptom inventories and neurocognitive assessments to capture an athlete's altered perceptual-motor ability, cognitive ability, and test these skills within a sport specific context. Perceptual-motor deficits include changes in motor reaction to a visual stimuli[53,97] oculomotor inefficiency[49–51,54] auditory, somatosensory, and vestibular perception.[14,15] Cognitive deficits include increased reaction time, visual and verbal memory,[25] and changes in brain resource allocation.[42,106] Cognitive deficits are also seen in dual-task literature as cognitive and motor task compete for resources which often results in changes in walking gait velocity.[23,26,48]

These deficits in perceptual-motor ability, support the direct perception theory that postulates how disruption in perception would break perception-action coupling and increase risk of subsequent injury[9] which could explain the increased musculoskeletal injuries.[9,91,92] Cognitive deficits within dual-task literature also emphasizes how individuals with a concussion history must prioritize certain task leading to changes in gait and inconsistencies in cognitive performance.[23,26,48] Finally, a study that replicated a sport-like environment using VR has shown how like environmental context can lead to significant changes in lower-limb injury risk landing biomechanics compared to a real a controlled laboratory setting.[36] Paired together, perceptual-motor deficits, cognitive deficits, and the limitations of sport context could be a large factors to subsequent injury risk.

To minimize this subsequent injury risk and to improve concussion assessment sensitivity, we proposed utilizing a dual-task paradigm incorporating a commonly used neurocognitive assessment of working memory (reverse digit-span task) and a perceptual-motor assessment (a target interception task founded in behavioral dynamics) within a sport relevant context (a VR environment). This study served as a novel approach to characterize perceptual-motor and cognitive ability in a previously concussed population while introducing the crucial, often neglected, sport like environment to increase the sensitivity of concussion return to play assessments.

CHAPTER 3

AIM 1 METHODS

Design

Aim 1 utilized an existing data set. The subset of data used was from a quasi-experimental, cross-sectional study conducted from 2019-2020. The study was conducted on healthy club sport athletes (no concussion history and individuals with a concussion history) at the University of North Carolina at Chapel Hill. Enrolled participants completed a consent form, demographic and health survey, and a reverse digit-span task within a VR environment. The study examined within and between group associations of task performance and physiological outcomes across the five levels of the reverse digit-span task and approved by the University's Institutional Review Board. Participants were compensated $10 for their time.

Participants

Study participation was available to all UNC club sport athletes, regardless of sport type, position, or current competitive season. Participants were eligible if they were between the ages of 18 and 30 and a rostered UNC club sport athlete. Additionally, participants were eligible for the concussion group if they self-reported having a prior concussion history after reviewing a definition for concussions and common signs and symptoms. Individuals were excluded if they did not meet the above inclusion requirements and/or if they had permanent vision loss in one or both eyes, had any visual surgery in the last year that would inhibit testing completion, were currently being treated to address balance or vision problems, and/or had strabismus or amblyopia. The prior study determined that for a multivariable model, 62 total participants with 30-40% of participants having a prior concussion history would be sufficient to power the study.

In total, 62 participants were previously recruited from 18 club sports and non-club sports from December 2019 to March 2020, where 2 were initially excluded from the study due to non-credible performance scores. Sixty participants were included in the secondary analysis (age: 20.48 ± 1.86 years; 26 females, 34 males). Sport participation included Men's Rugby (n=11), Softball (n=10), Hockey (n=8), Men's Soccer (n=7) and Rock Climbing (n=4). One participant in each sport category made up the rest of the 13 participants: Cheer, Swimming and Diving, Women's Soccer, Baseball, Golf, Gymnastics, Jiu Jitsu, Jump Rope, Marathon Running, Racquetball, Women's Lacrosse, and Cross Country. Of the 60 participants, 24 self-reported as having a concussion history (25% reported being 6 months to 2 years since their most recent concussion, 21% reported 2 to 3 years since their most recent concussion, and 54% reported being more than 3 years since their most recent concussion.[115]

Of those 60 participants collected, 7 participants were excluded as their 3-span recall accuracy fell below 100%. It was reasoned that if an individual was unable to complete a 3-span recall, they were not giving their full effort in completing the task. In addition, clinical utilization of the SCAT5 includes a working reverse digit recall assessment[62] which would cause concern to practicing clinicians if an athlete was unable to achieve this lowest level of cognitive working memory. As a result, 7 participants (2 concussion and 5 healthy controls) were excluded due to their 3-span recall accuracy falling below 100%. Following this, descriptive analyses were conducted to determine whether the assumptions of normality and homogeneity of variance for our analytical approach were met. In doing so, 3 additional participants were removed from the concussion group due to being extreme outliers (mean ± 1.5 SD) prior to analysis. Thus, the final analysis consisted of 50 participants (31 healthy, 19 concussion).

Procedures

Participants completed a demographic and health history survey followed by a reverse digit-span task within a VR environment in the prior study. The entire study took approximately one-hour where participants were seated in a chair and fitted virtual reality headset.

Reverse Digit-span Task

The reverse digit-span task was then explained to participants while in the VR environment, followed by 4 practice trials (all 5-digits in length) to familiarize them with the task. The reverse digit-span task consisted of the visual presentation of a series of single-digit numbers, which participants were asked to remember and verbally recall in the reverse order from which they were originally presented. Participants were given compliance feedback (e.g., appropriate response timing, trial initiation accuracy, etc.) during practice, and encouraged to ask any questions they may have had about the testing procedures prior to beginning the experimental trials.

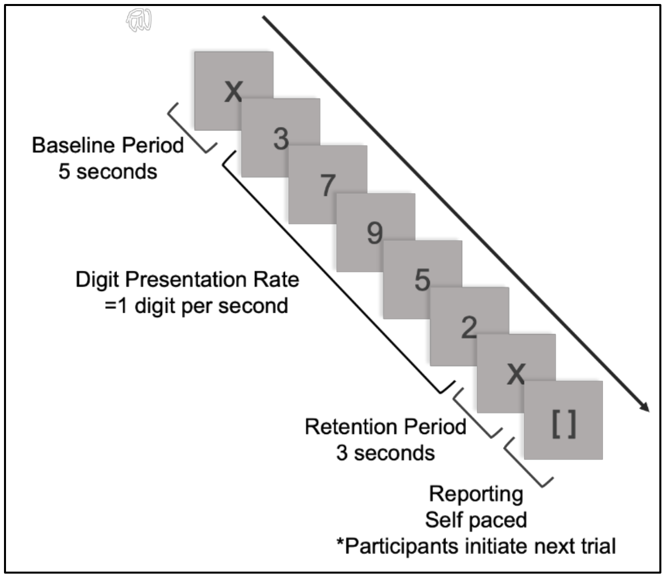

Figure 2. Reverse Digit-Span Task Presentation

The figure above displays how a single reverse digit-span trial (the second lowest difficulty level consisting of 5 digits in length) was conducted. Participants were provided with a 5 second baseline period “X”, followed by single digits presented at 1 digit per second. A 3 second retention period “X” followed the last digit presentation so participants could process the information followed by a self-paced reporting period “[ ]”

Sequence-lengths for each trial was 3, 5, 7, 9, or 11 digits long. Participants were asked to recall as many digits as they could possibly remember (in exact reverse order), for each trial. Figure 2 descirbes how a 5-digit-span length was conducted. Reporting periods were self-paced, and all trials were participant initiated using the HTC VIVE handheld controller triggers. No feedback was provided during experimental trials.

Overall task design consisted of 4 consecutive testing blocks of 5 randomized sequence-lengths (i.e., 3, 5, 7, 9, and 11)—20 total trials (Figure 3). Sequence-length presentation order within the first testing block was determined using a random number generator followed by a Latin Square to counter-balance sequence-length presentation order for the remaining 3 blocks.

Task Performance

Participant verbal recall was recorded by research assistants in a speadsheet. A custom Matlab Script (MATLAB and Statistic Toolbox Release 2017b, The Mathworks, Inc., Natick, MA, USA) was used to extract and analyze data. Cognitive performance was baed on serial positining and was given a percent correct based on the number of dgits provided.

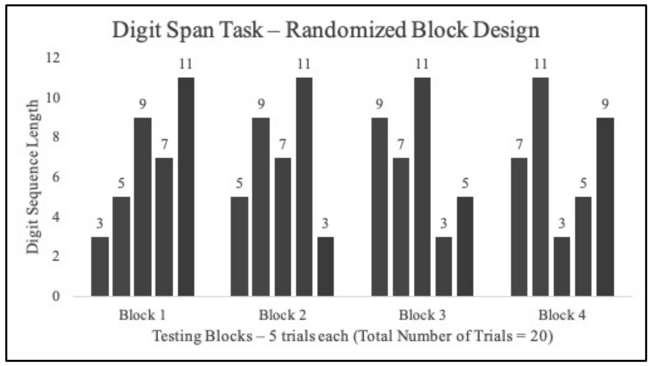

Figure 3. Randomized Block Design

Measure/Materials

HTC VIVE VR

The custom developed digit-span task was developed using Unity 3D® engine software, to be visually presented within the HTC VIVE™ (©2020 HTC Corporation) VR head-mounted display (HMD). Dual AMOLED 3.6” 1080x1200 HMD with a frequency refresh rate of 90Hz.[116]

Analysis

A new method of analysis was used to analyze the previously collected data set. This analysis was adapted from Hill and colleagues’ performance loading assessment to calculate cognitive adaptability.[90] Performance scores during the reverse digit-span task was binned by level of difficulty, with the lowest level (3 digit-span) being the baseline score. Performance scores from subsequent levels of difficulty/load were then normalized with the baseline score to equate a response score that was then plotted as on load-response curve pictured in Figure 4.

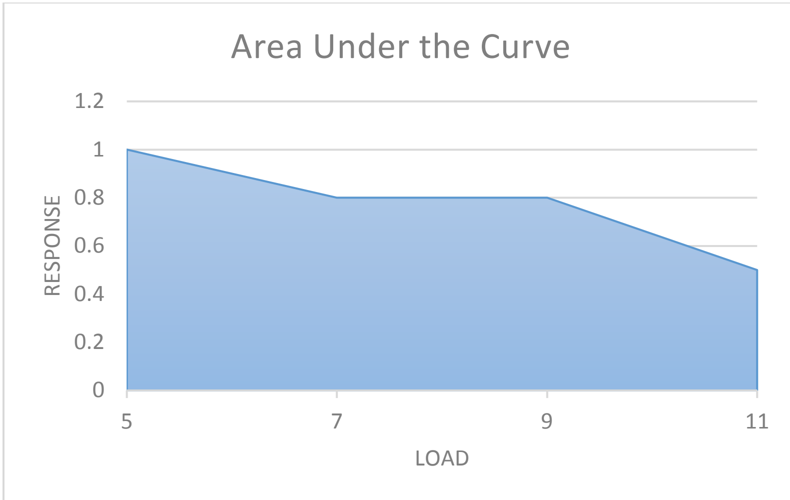

Figure 4. Area Under the Curve

An example of Area under the curve (AUC) is demonstrated above. AUC was calculated by computing a response score from subsequent performance scores over the 3-digit-span length baseline score. Response scores were plotted and the summation of response scores equated the AUC.

$$Response = \frac{performance}{Baseline}$$

After plotting the load-response curve, the area under the load-response curve (AUC) quantified each participants' cognitive adaptability across loads for each block of testing. AUC values were then be averaged in each group and compared using an independent samples t-test.

AIM 2 METHODS

Design

Aim 2 recruited 30 participants as part of a cross-sectional study design, fifteen in the control group and 15 in the concussion history group. Participants were initially screened and assigned to the concussion history group or the healthy controls group based on criteria detailed below. Once enrolled, all participants completed a one-hour testing session where participants consented, completed a demographic survey, and a dual-task cognitive and perceptual-motor assessment.

Participants

Participants were eligible if they are between the ages of 18-30 years, physically active, constituted by participation in a minimum of 30 minutes of moderate physical activity, as described by the American College of Sports Medicine, three days a week.[117] Participants were eligible for the concussion history group if they self-reported that they were diagnosed with a concussion by a medical profession (physician, athletic trainer, physical therapist) at any time during their playing career. Exclusionary criteria for this group included: if they did not meet the inclusion criteria, if they have not been cleared to return to activity after a concussion, or if they did not pass the screening questions for active symptoms assessed using the Rivermead Post-Concussion Symptoms Questionnaire. The exclusionary criteria for both groups included if the participant had a history of cardiovascular/pulmonary abnormalities, had eye surgery or eye movement/alignment abnormalities, sustained a lower extremity injury within the past 6 months, a history of lower extremity surgery, neurocognitive deficits (including ADD/ADHD, dyslexia, learning disability), or chronic ankle instability. All participants consented prior to testing and could withdraw from the study at any point for any reason. Concussion was defined using the Consensus Statement on Concussion in Sport from the 5th International Conference on Concussion in Sport as a functional brain injury that is typically induced by biomechanical a cascade of short-lived neurological and neuropathological changes.[118]

Similar to Aim 1, the 3-span recall accuracy during the digit-span only task was considered the baseline measure for digit-span recall. Participants were allowed one trial that was not 100% accuracy, and in the event that one trial occurred below 100%, it was dropped. One participant was excluded as their 3-span recall accuracy fell below 100% (accomplishing only 2 of the 4 trials at a 100% accuracy during the single task recall). Two other participants had a single trial below 100%, however they were both included in the analysis as the majority of their trials were at 100%. The baseline 3 span accuracy of these two participants was adjusted to reflect a 100% accuracy and their AUC scores were adjusted accordingly. Thus, 30 participants were included in the final analysis, with 15 healthy and 15 with a concussion history. Participants' average age was 19.8 ± 1.58 years, and 22 were male.

The 21 participants consisted of participants who primarily identified as soccer players, 8 participants who identified their primary sport being football (n=2), basketball (n=2), softball (n=2), cheerleading (n =2), and one swim/dive. Of the participants in the concussion group, four reported losing consciousness (28.57%), 9 reported recovery within 2 weeks (64.29%), five reported recovering within a month (35.51%), and average self-reported time from last concussion was 4.64 ± 3.14 years.

No prior study has investigated mean change in bearing angle in a concussion population before. Despite not having reliability and power analysis available, a similar study by Powers and colleagues recruited a sample size of nine concussed participants and nine healthy controls to investigate dynamic stability and steering control.[119] Although the study did not investigate mean bearing angle, it did investigate trunk roll angle between groups. Based off the data needed reach dynamic stability margin between groups ($F(1,16) = 5.95$, $p = 0.027$, Cohen's $d = 1.15$), we estimated that a total sample size of n=14 (7 without a concussion history and 7 with a concussion history) would be sufficient to power our study with 95% confidence. Therefore, we recruited 30 participants in total, 15 without a concussion history and 15 with a concussion history.

Procedures

The institution's Office of Human Research Ethics board approved this study. Participants provided written informed consent prior to completing a one-hour testing session. Participants completed a demographic and medical history questionnaire that included specific questions regarding their concussion injury history (see Appendix A and B). Participants were then be fitted with a wireless VR head set (Oculus Quest VR) and adjustments were made to ensure that the participant can achieve vergence in the headset to replicate normal vision in the real world before starting the assessments.

The assessment consisted of 2 testing blocks: 20 trials of single-task reverse digit-span recall and 28 trials that consist of single-task target interception and dual-task reverse digit-span with target interception as depicted in Figure 5 and described in more detail below.

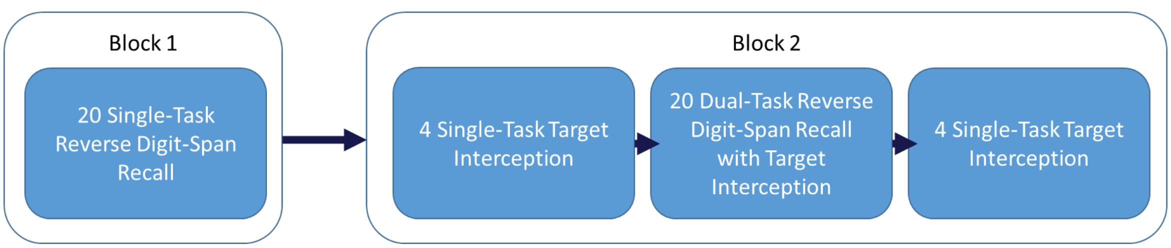

Figure 5. Design Procedure

Participants completed complete block 1, 20 trials of single-task reverse digit-span recall. This is followed by Block 2 that consisted of 28 total trials. The first 4 trials were single-task target interception, followed by 20 consecutive trials of dual-task reverse digit-span recall with target interception, and ended with 4 single-task target interception trials.

Reverse Digit-span Task

The reverse digit-span task that used was adapted from the prior mentioned study and from Johnson et al.[55] The reverse digit-span task utilized the same overall task design as described in Aim 1 with the main differences being in the VR headset used.

Once participants entered the VR environment the testing procedures were explained to them. Participants were visually presented with a series of single-digit numbers and asked to remember and verbally recall the numbers in the reverse order originally presented. They completed 2 practice trials (all 3-digits in length) to familiarize them with the task. Feedback during practice, and encouraged to ask any questions they may have about the testing procedures prior to beginning the experimental trials.

Overall task design, replicated the previous study. It consisted of a randomized blocked design containing five levels. Each level corresponds to the digit-span length presented (3, 5, 7, 9, or 11 digits long). Digits were randomly selected to eleven digit-span lengths. Four consecutive testing blocks of randomly generated digit-sequence lengths were computer generated, per block, per subject. These digit sequence lengths were chosen based on previous concussion literature, in order to overload individuals within this age range beyond their working memory capacity (i.e., normal memory capacity is approximately seven digits).[55,120]

Target Interception

The target interception task was adapted from Fajen and Warren[41] and was used to assess their perceptual-behavioral abilities. To start the assessment, participants wore the Oculus Quest VR headset and positioned themselves in an origin meter square box. Participants were then tasked to run and intercept a moving target at a constant speed perpendicular to their line of sight as depicted in Figure 1. The speed of the moving target was standardized to 80% of participants determined top speed, as computed based on 4 trials of the athlete running to a stationary target in VR. Task instructions were provided and participants completed 2 practice trials prior to starting the single-task interception. Target trajectory alternated going right to left and vice versa. Participants completed 8 trials of single-task target interception, 4 trials occurring at the beginning of block 2 and 4 trials that end block 2.

Dual-task Stimulus Presentation

Participants then completed a dual-task assessment where they completed the reverse digit-span task and subsequently the target interception task (i.e., 3 digit-span task and running to a moving target) as seen in Figure 1. Test administrators started each trail when participants are within the meter squared box and communicate that they were ready. Participants were given instructions to run to the target as fast as possible while also reporting the reverse digits as accurately as possible.

Each trial started by presenting the participants with a baseline period that lasted three seconds, indicated by an "X." Afterwards, a pseudorandom testing level was presented (3-digit, 5-digit, 7-digit, 9-digit, 11-digit), which displayed the corresponding digit-span at a rate of one digit per second. After the final digit was presented, a three second retention period and count down was provided to indicate the start of the interception task. This allowed participants time to process the information and not to prioritize the running task over the cognitive task. After this period participants were immediately presented with a moving target to intercept. They were then instructed to run at a meet the target before it reached the corner of the field. Once participants reached the target, were visually prompted to verbally recall the numbers in the reverse order in which they were presented for that trial. Participants completed four consecutive testing blocks, for a total of 20 trials.

Task Performance

Study personnel entered participants' verbal responses into a digital survey. Task performance accuracy was determined by serial position, where for each number recalled in the correct serial position, the participant received credit.[45] Participants were required to achieve at least 100% accuracy in 3 out of the 4, 3-span loading to ensure participant engagement and full effort in completing the task.

Measure/Materials

Quest VR

The Oculus Quest (Oculus VR, LLC) was the virtual reality headset used in testing. The system consists of a fully wireless Dual OLED 1600x1440 HMD with a frequency refresh rate of 72Hz,[121] a 3648mAh rechargeable lithium ion battery, and has an overall weight of approximately 70g.[122]

Analysis

MATLAB was used to reduce, filter and summarize the raw data. JASP 0.12.0.0 was then used to analyze processed data. Each participant received an average accuracy and an average standard deviation change in $\dot{\beta}$ for each of the five levels of the task (three digits, five digits, seven digits, nine digits, eleven digits). Accuracy was calculated for each trial, binned by difficulty, and standardized to the baseline performance score. This ratio was then be plotted and AUC was be calculated for each participant and compared between groups using a repeated measures two-way ANOVA. Changes in bearing angle was averaged in each group and binned by task level to compare testing groups using a repeated measures two-way ANOVA for each of the performance measures.

During the repeated measures two-way ANOVA for Aim 2, Mauchly's test of sphericity indicated that the assumption of sphericity was violated. Initial statistical analysis indicated a substantially positive skewedness over 1.5 that violated statistical assumptions. To correct this, a log transformation was applied to ensure that the bearing angle ($\dot{\beta}$) data conformed to normality. All statistical analyses were conducted on the transformed data, while all reported means and standard deviations are the non-transformed values.

CHAPTER 4

RESULTS

Aim 1

Demographic information is described in Table 1. A significant difference in the AUC scores was found, t (48) =2.148, p = .037; Cohen's d = 0.626, with individuals with a concussion history exhibiting a lower AUC (2.523 ± 0.537) compared to those individuals without a history of concussion (2.884 ± 0.599) as further described in Table 2 and 3.

Demographics	***Male***	***Female***	***Total***
Concussion History	13	6	19
Controls	15	16	31
Self-reported number of concussions			
1	8	4	12
2	4	1	5
3+	1	1	2
Age in years (SD)	20.75 (1.90)	20.1 (1.15)	20.46 (1.63)
AUC	2.78 (.533)	2.70 (.682)	2.75 (.60)
N	28	22	50
Note. Standard deviation = SD; Area under the curve = AUC			

Table 1. Aim 1 Demographics

Independent Samples T-Test				
	t	**df**	**p**	**Cohen's d**
Area Under the Curve	2.148	48	0.037	0.626

Table 2. Aim 1 Independent Samples T-Test Results

Group Descriptive					
	Group	**N**	**Mean**	**SD**	**SE**
Area Under the Curve	Control	31	2.884	0.599	0.108
	Concussion History	19	2.523	0.537	0.123

Table 3. Aim 1 Group Descriptives

Aim 2

Digit-span Recall AUC

Demographic information for Aim 2 is described in Table 4. No significant effects of concussion history were observed for AUC scores during single (No concussion history = 1.54 ± .36; Concussion = 1.62 ± .3) or dual-task conditions (No concussion history = 1.35 ± .34; Concussion = 1.49 ± .35), F (1,28) = .198, *p* = .66. However, a significant main effect of task type was observed, F (1,28) = 6.82, *p* =.014, indicating significantly higher AUC scores for all participants during single-task digit-span recall (1.584 ± 0.330) compared to dual-task digit-span recall (1.418 ± 0.347) as described in Table 5 and 6.

Demographics	**Male**	**Female**	**Total**
Cheerleading	0	2	2
Basketball	2	0	2
Football	2	0	2
Soccer	18	3	21
Softball	0	2	2
Swim/Dive	0	1	1
Control	11	4	15
Concussion History	11	4	15
Mean no. of concussions (SD)	1.09 (.302)	1.5 (.578)	1.2 (.414)
Mean time since last concussion in years (SD)	5.10 (3.25)	3.38 (2.82)	4.64 (3.14)
Age in years (SD)	19.682 (1.615)	20.125 (1.553)	19.8 (1.58)
N	22	8	30
Note. Standard Deviation = SD			

Table 4. Aim 2 Demographics

Within Subjects Effects						
Cases	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**	**η²**
Task	0.413	1	0.413	6.820	0.014	0.059
Task ∗ CxHx	0.012	1	0.012	0.198	0.660	0.002
Residuals	1.697	28	0.061			

Between Subjects Effects						
Cases	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**	**η²**
CxHx	0.178	1	0.178	1.045	0.315	0.025
Residuals	4.764	28	0.170			
Note. Concussion History = CxHx						

Table 5. Aim 2 Area Under the Curve ANOVA table

Post Hoc Comparisons - Task							
		Mean Difference	**SE**	**t**	**Cohen's d**	**p bonf**	**p holm**
Single	**Dual**	0.166	0.064	2.612	0.477	0.014	0.014

Table 6. Table 6. Aim 2 Area Under the Curve Post Hoc Analysis

Mean SD in Bearing Angle ($\dot{\beta}$)

No significant effects of concussion history were observed for the average standard deviation in the change in $\dot{\beta}$ for single or dual-task conditions, F (1,28) = .103, *p* = .751. There were also no significant interaction effects, F (1,140) = 1.646, *p* = .152.

However, a significant main effect of task type was observed, F (1,140) = 4.597, p <.001 as seen in Table 7. Follow-up t-tests using a Bonferroni correction, found a significant difference between single-task target interception (.185° ± .239°) and dual-task 9 digit-span recall (.551° ± .757°) during interception (t (28) = -4.031, p = .001; Cohen's d = -0.736); as seen in Table 8. There were no other significant differences between task, however single-task target interception (.185° ± .239°) and dual-task 7 digit-span recall with interception (.485° ± .722°) (t (28) = -3.275, p = .019; Cohen's d = -0.598); and dual-task 3-span recall with interception (.224° ± .25°) and dual-task 9 digit-span recall with interception (.551° ± .757°) (t (28) = -3.060, p = .034; Cohen's d = -0.559) exhibited a non-significant trend in the hypothesized direction of increased $\dot{\beta}$.

Within Subjects Effects						
Cases	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**	**η²**
Task	2.098	5	0.420	4.597	< .001	0.051
Task ∗ CxHx	0.751	5	0.150	1.646	0.152	0.018
Residuals	12.778	140	0.091			
Between Subjects Effects						
Cases	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**	**η²**
CxHx	0.093	1	0.093	0.103	0.751	0.002
Residuals	25.350	28	0.905			
Note. Concussion history = CxHx						

Table 7. Aim 2 Mean Standard Deviation in the Change in Bearing Angle ANOVA table

Post Hoc Comparisons - Task						
		Mean Difference	**SE**	**t**	**Cohen's d**	**p holm**
Single Task Interception	**3-Span**	-0.076	0.078	-0.971	-0.177	1.000
	5-Span	-0.140	0.078	-1.793	-0.327	0.601
	7-Span	-0.255	0.078	-3.275	-0.598	0.019
	9-Span	-0.314	0.078	-4.031	-0.736	0.001**
	11-Span	-0.226	0.078	-2.892	-0.528	0.053
3-Span	**5-Span**	-0.064	0.078	-0.823	-0.150	1.000
	7-Span	-0.180	0.078	-2.305	-0.421	0.249
	9-Span	-0.239	0.078	-3.060	-0.559	0.034
	11-Span	-0.150	0.078	-1.921	-0.351	0.511
5-Span	**7-Span**	-0.116	0.078	-1.482	-0.271	0.984
	9-Span	-0.175	0.078	-2.237	-0.408	0.269
	11-Span	-0.086	0.078	-1.098	-0.201	1.000
7-Span	**9-Span**	-0.059	0.078	-0.755	-0.138	1.000
	11-Span	0.030	0.078	0.384	0.070	1.000
9-Span	**11-Span**	0.089	0.078	1.139	0.208	1.000

Note. *P* value was adjusted for multiple comparisons, $p < .01$ reflect significant differences.
* $p < .01$

Table 8. Aim 2 Mean Standard Deviation in the Change in Bearing Angle Post Hoc Testing

CHAPTER 5

DISCUSSION

The purpose of this study was to simulate a sport-like environment (through the application of a dual-task paradigm performed in VR) in order to examine perceptual-motor and cognitive deficits that are known to persist following concussions.[24,42,43,49–54] Our first aim was to evaluate an athlete's adaptability using a method from load-response dynamics[46,90] to quantify an athletes cognitive recall capability across workload, as a method for increased sensitivity to detect cognitive deficits following concussion. Our second aim was to evaluate perceptual-motor deficits in previously concussed individuals. We utilized a behavioral dynamics framework and evaluated the average standard deviation in $\dot{\beta}$ during athletes' performance intercepting a moving target in the presence and absence of the digit-span recall task. The overall goal was to observe the interacting effects of cognitive and perceptual-motor deficits that may impact an athletes' injury risk as they return to play following a concussion injury.

Aim 1

To accomplish our first aim, we utilized previously collected data and computed the area under the curve (AUC) to quantify an athlete's memory recall adaptability during a digit-span recall task in athletes with and without a concussion history. The results supported the primary hypothesis that this AUC metric would provide greater sensitivity to group differences compared to traditional digit-span recall scoring. Specifically, the results indicated that individuals with a concussion history exhibited less adaptable recall performance relative to 4 levels of increasing demand compared to controls without history of concussion.

The utilization of AUC expands on the method of computing biologic (e.g., phenotypic) plasticity by Calabrese & Mattson.[46] This approach is based on the idea that biological organisms respond to environmental stressors (or loads) in variable, non-linear ways. While this approach has not been applied to a concussion population prior to this study, it provides a more comprehensive way to assess how the cognitive system is able to respond in the face of changing loads. In the secondary analysis, increasing cognitive loads resulted in positive performance scores which decreased as loads increased, that were identified via a load-response curve as expected. The concussion history group exhibited a diminished area under the curve indicative of a decreased cognitive recall adaptability across increasing workloads as seen in example in Figure 6.

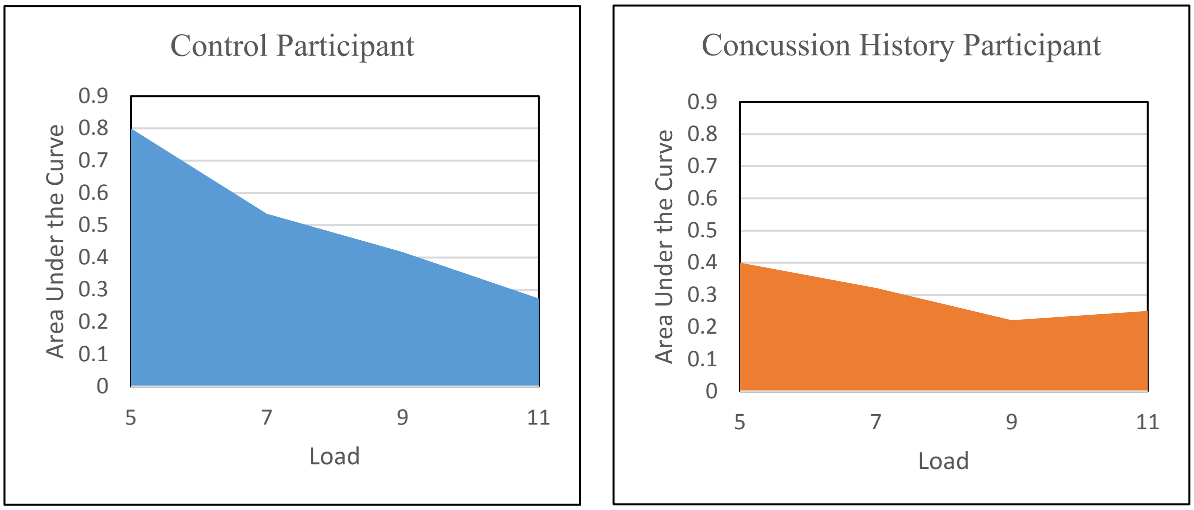

Figure 6. Area Under the Curve of Example Healthy and Concussion Participants

The graphs above depict two load response curves for a single participant in the control (left graph) and the concussion history (right graph).

Importantly, the original study findings by Vander Vegt[115] did not indicate significant differences in traditional performance scores between groups. The reverse digit-span recall task used in Vander Vegt's study has been used extensively in the SCAT5 as part of the short-term memory concussion asessment.[55–57] Studies that utilize cognitive working memory assessments have found a variety of group differences based on traditional task performance. For example, traditional performance scores of athletes following concussion indicate long term cognitive deficits that extend beyond the typical 7-10 day return to play window. Specifically, Keightley[43] reported that concussed youth had worse performance scores on working memory compared to matched healthy controls up to three months post injury.[43] This trend was also demonstrated in a study by Moore that also looked at a pediatric population and found that concussed individuals (averaging 2.1 ±1.9 years post injury) had more omission errors during cognitive testing compared to healthy counterparts, and these individuals also exhibited concomitant changes in EEG patterns.[105] Part of the reason that Vander Vegt's study did not support the observed differences by Keightley or Moore could be attributed to Vander Vegt's study having larger variation in time since concussion injury: 54% of participants reported being more than three years since their most recent concussion.[115] This is in sharp contrast to Keightley's three months post injury[43] and slightly higher than Moore's mean 2.1 ±1.9 years post injury.[105]

These inconsistencies may be partially explained by the results by McAllister et al.,[42] which found that in a working memory task the concussed group did not significantly differ in their performance scores from the no concussion history group.[42] However, the concussion group had increased brain activation, as seen visually through fMRI, during moderate loads, and lower activation with highest loads compared to no concussion history controls. The authors proposed two possible explanations for this mismatch of brain activation and traditional working memory performance.

One explanation was that concussed participants had working memory capacity impairments/efficiency, but the study did not demand a cognitive load difficult enough elucidate the between-group differences on task performance. However, concussed individuals still had to recruit additional processing resources (through the activation of other areas of the brain) to compensate for these sub-clinical inefficiencies while healthy controls were not impaired and did not need to increase resources. It was further explained that at the highest difficulty load, controls were able to continue increasing activation as they had remaining reserves, while the concussed group (inefficient at working-memory) already used up most of their resources and therefore had little activation during the higher loads.

The second explanation was that working memory capacity was not impaired between groups, which would explain the similar performance scores. However, the concussed participants still had deficits in the ability to match the processing of their own resources (brain recruitment) to the difficulty of processing load, which the authors termed *impaired allocation of resources*. This would explain why the concussed group was mismatching moderate difficulty loads with increased commitment of resources and high difficult loads with little increased commitment of resources.[42]

The results of our secondary analysis support McAllister's second explanation. Vander Vegt's study provided participants with 5 degrees of difficulty (3, 5, 7, 9, 11 digits),[115] which provided enough cognitive overload to see differences in working memory provided that more recent studies claim working memory capacity is limited to 3 to 5 meaningful items.[123] As both no concussion history and previously concussed groups had similar performance scores, working memory capacity was not impaired. Rather, the inconsistency in scores support the concept of *impaired allocation of resource*s, in that concussed participants had difficulty matching their own processing resources to processing loads. This would explain the decreased AUC, as with 5 different levels of processing loads, participants had even more difficulty in matching and anticipating their resources to various randomized working loads. This resulted in their decreased ability to adapt to various levels of the task compared their no concussion history controls. As AUC provided a cumulative measure of adaptive performance across all loads rather than between individual loads, this score of adaptability could be reflecting the participants inability to match processing resources to various working loads—something that would not be picked up, statistically, when comparing within a single load. Essentially, an athlete's overall ability to adapt to various workloads is important to consider in addition too traditional performance scores.

The results of these studies also potentially indicate that traditional cognitive scoring on short-term memory, specific to a given workload may not encompass all an athlete is required to do to process sport strategy. Short-term memory may reflect an individual's ability to immediately remember plays, but athletes must also hold on to playing information while being able to adapt this knowledge to movement on the field. Therefore, an athlete's adaptability should be a strong consideration, in addition to performance accuracy and this new AUC analysis may provide greater insights on adaptability without the use of expensive imaging equipment. To our knowledge, the present study is the first of its kind to implement a novel analysis that comprehensively accounts for performance across various cognitive loads within a concussion history population. These findings indicate that AUC as a measure of adaptability may provide greater sensitivity for concussion assessments. Therefore, future research should also consider such an approach to characterize the behavioral adaptability of individuals with a concussion history.

Aim 2

The second aim of this study was to investigate if individuals with a concussion history had less adaptable performance across cognitive workloads while performing a dual-task digit-span recall and target interception task. As part of this aim, the former digit-recall assessment used by Vander Vegt[115] was adapted to a dual-task paradigm, and the same AUC analysis was utilized to characterize adaptable performance. While it was hypothesized that the concussion group would exhibit lower AUC values across both the single and dual task conditions, no significant group differences were observed for either condition. There was, however, a significant main effect of task type, where dual-task digit-span recall resulted in significantly lower AUC scores than single-task digit-span recall irrespective of group. This suggested that participants were less adaptable to increasing workloads when also performing the target interception task. This aligns with much of the dual-task literature indicating decreased cognitive performance during the performance of a motor task.[48] This is also supported by a variation on the posture first hypothesis, which suggest that when presented with a dual-task, the preference is to prioritize walking/balance (or in our case interception) over the cognitive component.[124] Previous dual-task literature also suggest that cognitive and motor tasks must "compete" for resources during these paradigms.[107,108] Therefore, despite our hypothesis not being supported, our result supports the use of AUC to generally quantify an individual's adaptability during dual task performance .

The perceptual motor efficiency was also examined via mean changes in the standard deviation in $\dot{\beta}$ during both single- and dual-task interception. As prior studies have indicated an increased risk of concussion reinjury and increased risk of lower extremity injury[6] following concussion, it was postulated that concussion injury would result in long term perceptual-motor deficits and, more specifically, in the disruption of an athlete's ability to efficiently intercept a moving target—a proxy for athletic performance and injury avoidance.[9] However, our results did not support our hypothesis and the findings indicated that concussion history had no statistical effect on the average standard deviation in $\dot{\beta}$ during performance in single or dual-task contexts.

Despite this, we did find a significant main effect of task type, where across groups single-task target interception had a significantly smaller average standard deviation in $\dot{\beta}$ compared to dual-task 9 span recall were significantly different. In addition, there were some findings of interest relative to overall single- vs. dual-task performance and perceptual-motor efficiency. In general, mean standard deviation of bearing angle ($\dot{\beta}$) was the smallest during single task interception (0.185 ± 0.239) and increased up to (0.551 ± 0.757) during the 9 digit-span recall tasks, independent of group. Post-hoc test also indicated that independent of group, participants' single task interception trended towards more efficient performance when compared to average standard deviation of bearing angle ($\dot{\beta}$) of dual-task 7 digit-span. This was also true for the dual-task 3 digit-span and dual-task 9 digit-span conditions.

The lack of a group difference in the AUC finding failed to replicate the results of Aim 1, in that concussion history (a) had no effect on cognitive adaptability during single nor dual-task assessments and, likewise, (b) had no effect on perceptual motor efficiency of intercepting a moving target in the presence or absence of a secondary cognitive task. One explanation as to why no significant between group differences were identified could be that the concussion history group's time since injury was too large. Studies that have indicated an increased risk of concussion reinjury and lower extremity injury within one year post injury.[5,6] Provided that our average time since last concussion was 4.64 ± 3.14 years, it is possible that these individuals may have fully recovered and therefore had full perceptual-motor and cognitive capabilities. Although Vander Vegt's study reported a similar time from concussion, 54% of participants reported being more than three years since their most recent concussion,[115] that study included twice as many participants as the current Aim 2 study, which may have contributed to the lack of between group differences. Future studies should investigate mean standard deviation of bearing angle $\dot{\beta}$ within a narrower range of post injury, ideally no later than one year post injury, and with a larger sample size to examine differences between groups.

It is widely accepted that the working memory capacity is 7+/-2 bits of information.[125] However, Farrington argues this is misinterpreted and cites that more recent sources suggest that working memory capacity is typically only three to four items.[123,126,127] Regardless, this demonstrates that our participants were at and beyond the upper limits of previously accepted working memory capacity, and it reasons that 7 digits and beyond resulted in cognitive overload which may have resulted in an inhibition of perceptual-motor performance (i.e., larger mean $\dot{\beta}$ across groups). This also parallels the dual-task literature for motor performance, where it was concluded that individuals who sustain a concussion exhibit biomechanical gait impairments during dual-task assessments beyond the 7-10 day recovery time line.[26]

Interestingly, when we compare AUC between both studies, Aim 1 digit-span recall AUC was larger (2.75 ±.60) when compared to Aim 2 single-task digit-span recall AUC (1.584±.33), despite nearly identical task presentation. However, subtle differences in methodology could be a strong contributor to the differences in adaptability metrics. The main methodological factor that differed from the prior study was that participants completed the digit-span recall task while standing in a large open gym, compared to performing it in a seated position in a closed lab space in the prior study.[115] In addition, half of our participants completed the interception and dual-task assessments prior to the single-task digit-span recall assessment. Their fatigue due to running may have contributed to this lower cognitive adaptability as they transitioned from physical activity to cognitive working memory. Regardless of our methods counterbalancing standing digit-span recall and target interception, participants were never provided a seated position to rest from activity and focus solely on recall. Furthermore, despite both studies being completed in VR, the environmental context and testing space was drastically different. Our study was conducted in an open gym, which allowed us to create an open VR environment that replicated a low-fenced grass field. In contrast, the former study conducted their experimentation in a closed lab and the VR scene presented also reflected a gray enclosed lab space. As mentioned in previous literature, the environmental context can change motor behavior outcomes as seen in increased lower-limb injury risk biomechanics in a former VR study.[36] Both the alterations in task design and changes in the environmental context likely explains the lower AUC (decreased adaptability) in our results comparatively. Furthermore, this solidifies the importance of a sport specific environment with regards to evaluation post-injury deficits.

Despite the lack of significant differences between groups, our findings do suggest that cognitive overload may result in less efficient target interception. This partially supports the direct perception theory by Eagle and colleagues where fatigue induced by cognitive activity, or difficulty with cognitive activity results in an impaired affordance selection (i.e., decreased perception-action coupling).[9] However, our results do not directly support Eagle and colleagues prediction that individuals with a cognitive/fatigue symptom profile would result in completely disrupted perception-action capabilities, as the results of the current study indicate only a decrease in target interception efficiency across all subjects.

The present study was also not without limitations. First, the lack of AUC findings between groups could have been due to a limited sample size and our convivence sampling approach. Provided that the effect size was small ($\eta^2 = .025$), it is likely that our study was underpowered to find a true effect. In total, the final analysis of the present study included 30 participants. It should be noted that of those, a majority of participants were varsity college soccer athletes (n=18). Comparatively, the former study by Vander Vegt utilized a larger sample size (n=60) in addition to a larger breadth of sport variety (16 different sports in total) from various non-varsity sports.[115] In addition to the lack of sport diversity of subjects, 22 participants were male and 8 were female. As subjects were not gender-matched between groups, this provided the study with more generalizability, but decreased sensitivity in finding any changes between groups.

The study was also conducted without the inclusion of a physical fitness questionnaire, which could have played an important role in perceptual-motor efficiency. Participants enrolled in the study were required to be physically active three days a week for 30 minutes a day, without any metric of recording their weekly typical physical activity. Potentially, more active individuals like varsity soccer athletes could have skewed bearing angle data as more fit individuals would likely have greater endurance or technical running experience that could aid them in completing the entire task while minimizing fatigue. In addition, as our study was also populated by a large number of varsity soccer athletes, our results may have been skewed and less likely to identify changes in perceptual-motor efficiency as these athletes constantly practice and have become very familiar with an interception task (i.e., running to intercept a ball or tackling an opposing player). Lastly, the study did not restrict how far out from injury concussions had to be as stated previously. Prior studies have indicated that concussion reinjury[5] and increased risk of lower extremity injury may last up to a year post injury.[6] As the average time since participants' last concussion was 4.64 ± 3.14 years, participants were outside of the window of vulnerability and likely have fully recovered in their perceptual-motor ability. Ideally, future research should limit the most recent concussion injury history by at most a year out to better identify if perceptual-motor efficiency could be a contributor to secondary injury and concussion reinjury.

CONCLUSION

In summary, the AUC analysis approach shows strong potential for the differentiation of individuals with a concussion history from those without, and could aid in the improved sensitivity of similar cognitive assessments. Moreover, despite not finding any significant interactions between concussion history and the mean standard deviation of bearing angle $\dot{\beta}$, our dual-task paradigm does show promise in quantifying the perceptual-motor efficiency of participants during concomitant performance of a cognitive task. If utilized properly, it could have a place in concussion return to play and assessments, as it provides both a cognitive and perceptual-motor component, within a very important environmental context. Future studies should investigate both the analysis and paradigm in individuals who were more recently concussed (1 year out) to further investigate if perceptual-motor deficits are linked to concussion reinjury and lower-extremity musculoskeletal injury.

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